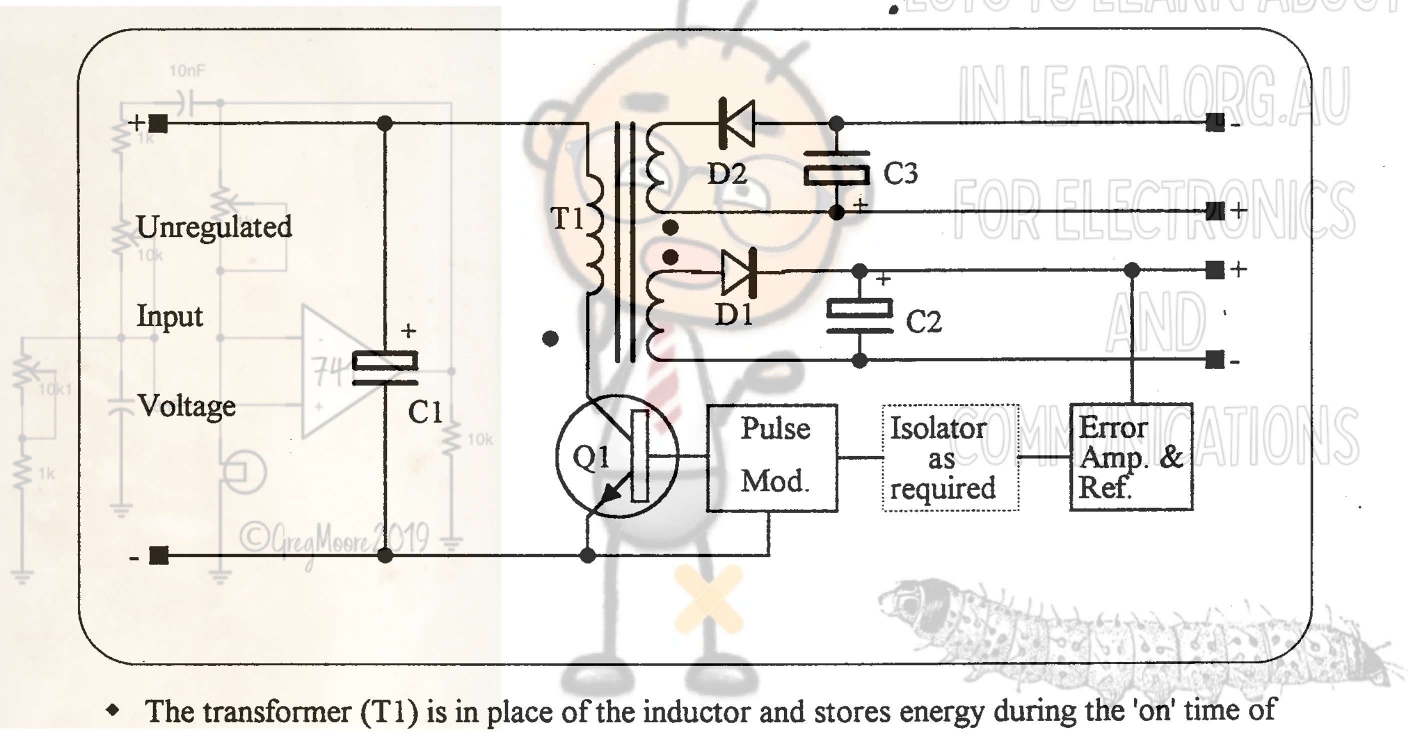
LESSON 8 - SWITCHED MODE POWER SUPPLIES - 3

TRANSFORMER COUPLED SWITCHED MODE REGULATORS

The type of output voltage is defined by the circuit configuration in previously discussed switched mode voltage regulators. By using a transformer operating at the switching frequency, it is possible to achieve step up, step down or polarity inverting outputs either individually or simultaneously. The transformer may be driven by the flyback mode where energy is transferred to the output circuit when the active chopper device is cutoff or it can be operated in a mode where energy is transferred when the active chopper device is driven to saturation. This latter is called a FORWARD mode regulator and requires an extra inductor to store energy for the output circuit when the active chopper device is cutoff.

FLYBACK TRANSFORMER COUPLED SWITCHED MODE REGULATOR



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- The transformer (T1) is in place of the inductor and stores energy during the 'on' time of the chopper transistor. The 'DOTS' indicate the same polarity of voltage swing.
- The energy in the transformer is transferred to the output filter capacitors by diodes D1 and D2. C3 is charged negative and C2 is charged positive.
- The positive output is monitored by the sensing resistors and controls the action of the error amplifier.
- If isolation between the unregulated input and the output is required, error information can be coupled back to the pulse modulator via an OPTO-ISOLATOR.
- The circuit is usually used in low power applications only.
- The transformer may be used to step up or step down as required with various voltage outputs.
- The transistor and diodes require to be fast switching types.

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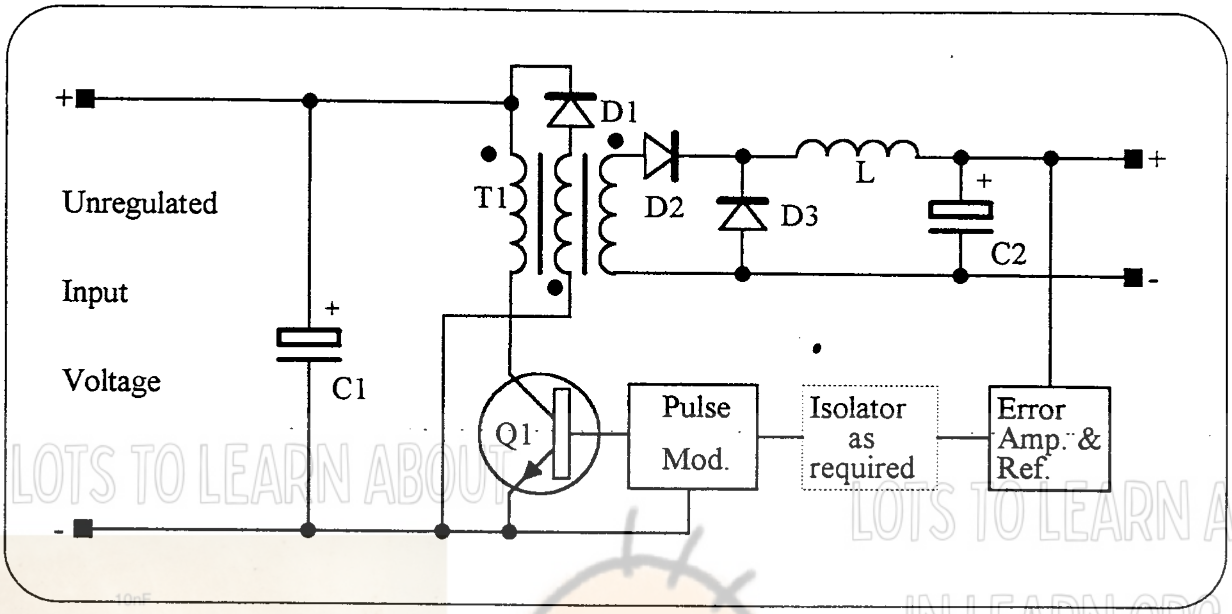
FORWARD MODE SWITCHING REGULATOR



- When the transistor Q1 conducts the transformer action of T1 causes D2 to conduct, transferring energy to the inductor L/capacitor C2 combination and also supplying current to the load.
- When the transistor Q1 cuts off, diode D2 ceases conduction and the energy in the inductor L transfers its energy to the capacitor C2 and the load with diode D3 completing the current path. Residual energy left in the transformer causes diode D1 to conduct, returning this energy to the input supply.
- Control is similar to previous systems, with isolation if desired.
- The transformer T1 requires a TRI-FILAR wound construction to reduce losses in this part of the circuit.
- The transistor Q1 is subjected to twice the input supply during its 'off' time and hence needs to allowed for in the design.
- The L/C2 components help to keep the ripple amplitude at the output to a minimum.
- The circuit is used mainly in low power applications.

The switched mode regulated power supplies discussed so far are all of the SINGLE ENDED variety and are mainly used in low to medium power applications due to the need to switch the input current through the chopper transistor. If heavy power is needed to run larger electronic systems, more than one transistor can be arranged in the chopper application when using the previously discussed transformer type switched mode regulators. This requires a more complex drive arrangement since each transistor must be driven on and off out of 'phase' with each other. Since the drive to each transistor is a square wave, with fast switching times there is a danger that one transistor is turned on before the other has completely turned off leading to loss of efficiency and high transistor dissipation. To eliminate this possibility, a DEAD BAND is arranged in the drive waveform of perhaps 5% of the period of the oscillator frequency to allow for 'switch off' for each of the transistors.

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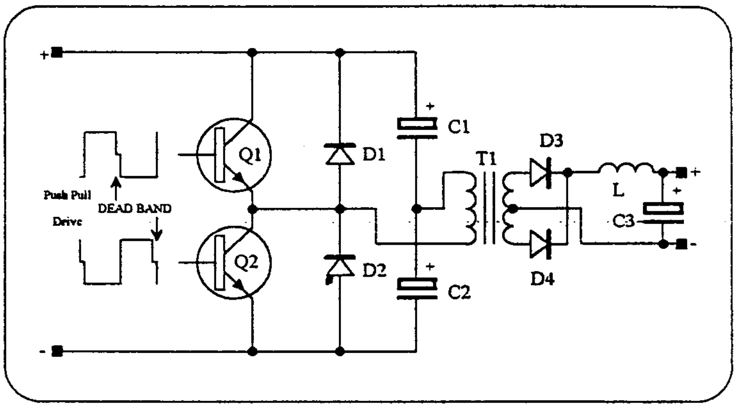
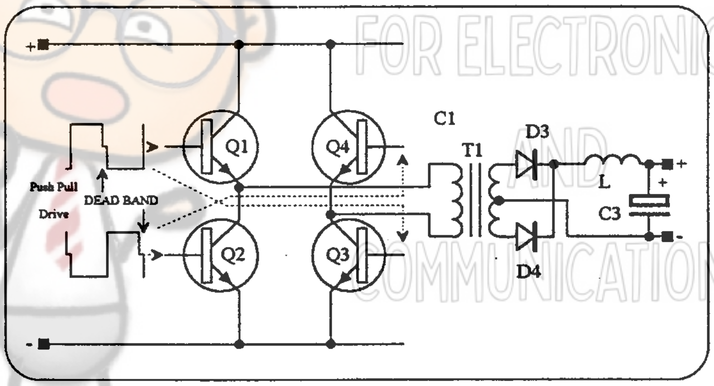
HALF BRIDGE CONVERTER



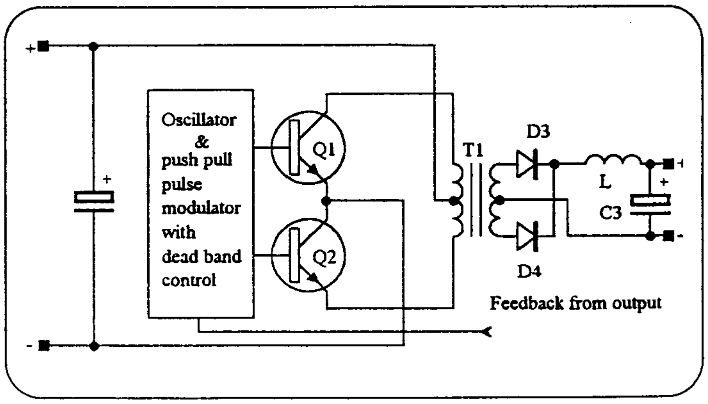
- The transformer has a single ended primary.
- Each transistor is made to conduct on alternate half cycles.
- D1 & D2 absorb any 'spikes' of voltage generated during the dead band period.
- Since energy is transformed each half cycle the output rectifier system can be of full wave configuration. A full wave bridge can be used instead of the centre tapped secondary form shown.
- The inductor L and capacitor C3 form a low pass filter to minimise ripple.
- The circuit is used for high power applications but the drive requirements involve a more complex drive circuit.
- Regulation can be obtained with previously discussed methods.

FULL BRIDGE CONVERTER



- Similar to the half bridge in operation except transistors Q1/Q3 conduct on one half cycle and Q2/Q4 conduct on the other half cycle and thus producing a full wave drive to the transformer T1.
- Requires a complex drive transformer with four separate windings that have to be phased correctly.
- The configuration is suitable for high output power requirements.

CENTRE TAPPED PUSH PULL CONVERTER



- By providing a centre tapped primary winding for T1, push pull operation can be arranged. This simplifies the drive requirements and no driver transformer is required.
- The circuit can be used for high power applications.
- Many IC regulators can be used in this configuration mode.

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OFF LINE POWER SUPPLY

An example of an 'off line' power supply is illustrated on page 85 of the student notes and the following points apply

- The MAINS supply is bridge rectified directly and charges the filter capacitor to near 340V dc.
- The configuration of the regulator is that of a forward converter with isolation of the feedback via an opto-coupler.
- The enhancement type IGFET must be able to handle the full dc input voltage.
- The power supply for the PWM control is from a separate rectifier that is isolated by coupling capacitors from the mains.
- Current overload is carried out by sensing the source current of the FET and will cause the system to shut down if the fet draws excessive current.
- The fast rectifiers in the output are further protected with spike reducing networks across them.

LOTS TO LEARN ABOUT

THE EQUIVALENT SERIES RESISTANCE OF FILTER CAPACITORS

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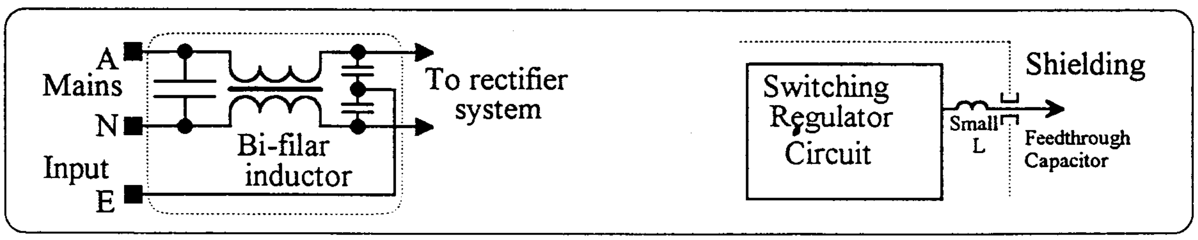
Electrolytic capacitors that are perfectly ok on 50 or 100 Hz ripple frequencies do not perform well at the higher switching frequencies. On investigation it was found that the typical electrolytic capacitor not only consists of a capacitance value but a small resistance value and a small inductance value that has two effects.

- The resistance component causes a voltage drop due to the charging and discharging of the capacitor under working conditions which leads to greater ripple amplitude at the switching frequency.
- At higher frequencies, the inductive component tends to cancel some of the capacitive reactance leading to poor bypassing performance.

The method of reducing the above effects is to use 2 to 4 parallel smaller capacitors to achieve the desired filter capacitance value which causes the parallel ESR effect to be smaller and to bypass the filter capacitors with a plastic capacitor of about 0.1µF which tends to counteract the inductive effect.

ELECTRO-MAGNETIC INTERFERENCE

Because of the fast switching of the active devices, a broad spectrum of frequencies can be radiated directly from the components or may be conducted on the mains input lines. The methods used to reduce these effects are to use full shielding of the power supply and small L/C filter components in selected points of the supply. The mains 'offline' supplies are usually filtered with a bi-filar wound inductor and capacitor combination called a HASH filter that reduces the interference to close electronic equipment that operate as communication systems.



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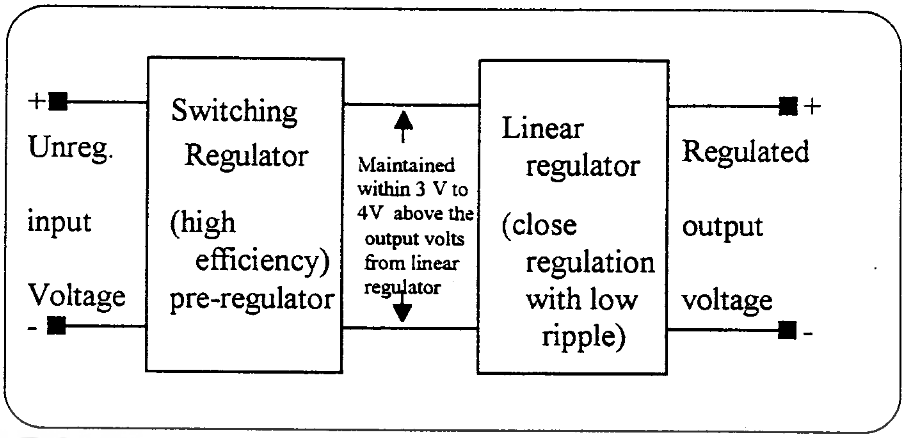
SWITCHED MODE CIRCUIT AS A PRE-REGULATOR

- The advantages of both types of regulator can be combined to give a well regulated supply with low ripple at the output.
- Variable bench power supplies sometimes use this technique.



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PRACTICE PROBLEMS

Q.1 Suggest reasons why a push pull converter is better for high power regulation compared to a single ended converter.

Q.2 State two advantages that a transformer type switched mode regulator has compared to a simple inductor type.

Q.3 List the important design considerations that must be given to 'off line' switched mode regulators.

Q.4 State why the output filter capacitance of a switched mode regulator may be constructed of several smaller values.

Q.5 Why is a large values electrolytic capacitor often bypassed by a much smaller plastic or ceramic capacitor ?

Q.6 Briefly describe the main differences between a flyback type regulator and a forward type regulator.

Q.7 State why a dead band is used in the drive waveform of a push pull or bridge type switch mode regulator.

Q.8 State the purpose of the 'free wheel' diode in a forward converter.

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ANSWERS TO PRACTICE PROBLEMS

Q.1 A push pull type converter conducts every half cycle and hence will reduce the average current through each transistor for a given output power requirement. This will mean that the chopper transistors can be of a lower power rating than the transistor for a single ended type converter. This in turn means that higher power can be delivered to the load for a given power rating of the transistors.

Q.2 i) Can be step up or step down or inverting without changing configurations.
ii) Can have multiple voltage outputs.

Q.3 i) The chopper transistor needs to be able to switch the 340V dc from mains rectification at the required current.
ii) A transformer type of configuration is necessary to achieve isolation from input to output. This entails some form of isolated coupling from the output back to the pulse modulator
iii) EMI input filtering is needed to minimise interference on the mains line.
iv) The filter capacitor for the mains rectifier is a large value with a high voltage rating.

Q.4 Electrolytic capacitors suffer from an equivalent series resistance that causes an increase in ripple and possible heating of the capacitor. The effects of ESR can be minimised by paralleling several smaller capacitors and hence reducing the problems.

Q.5 Electrolytic capacitors also tend to have an inductive effect the can cause a rise of its internal impedance at higher frequencies. A small plastic or ceramic capacitor has very little internal inductance that is a problem at the common switching frequencies and hence when parallel with the electrolytic the inductance becomes much smaller.

Q.6 A flyback regulator stores energy on the input stroke when the chopper is conducting and then transfers it to the output when the chopper is cutoff. The forward converter transfers its input energy when the chopper is conducting and uses an extra inductor to continue conducting while the chopper is cutoff.

Q.7 Fast switching transistors tend to be slower at switching off compared to switching on and hence a dead band is supplied to the drive waveform to allow for this. In a push pull or bridge configuration there is a danger of two transistors conducting and causing a dead short across the input voltage supply.

Q.8 When the single ended forward converter rectifier is cutoff, the inductor charged with magnetic energy needs to have a conduction path to allow a continuation of the load current. The reversal of the voltage across the inductor causes the free wheel diode to conduct and hence completing the load current path.

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ELECTRONIC TRADES - REGULATED POWER SUPPLIES - UEE30911

MODULE SUMMARIES AND TUTORIAL

LESSON 1. - INTRODUCTION

- Regulated power supplies are usually required to overcome the poor load and line regulation of rectified ac supplies. Ripple reduction is also a feature.
- To be effective, a regulated power supply must have a very low output impedance.
- To achieve regulation in practical power supplies, the regulator circuit must dissipate power in addition to load power.
- The equations for *LINE AND LOAD REGULATION* plus *RIPPLE REDUCTION FACTOR* are given in the lesson 1 notes.
- The *LINEAR SHUNT* regulator dissipates greatest power when the load current is zero but may be protected against short circuits if the series resistor is selected correctly.
- The *LINEAR SERIES* regulator dissipates least power when the load current is zero and the greatest power when the load current is a maximum but requires overload protection to avoid failure of components.
- All linear type regulators require an input voltage higher than the regulated output voltage.
- *SWITCHED MODE* power supplies have higher efficiency than linear power supplies and operate on high chopping frequencies which may cause interference in critical circuits.
- The SMPS can be made to step up, step down or invert the output voltage.
- All voltage regulators require an accurate and stable form of reference source such as a zener diode, selected LED or best of all a BAND GAP REFERENCE.

LESSON 2. - SERIES REGULATORS

- *SERIES* regulators use an active device such as a BJT or a FET in series between the load and the unregulated input voltage that can vary its impedance to compensate for the variation of load current and hence maintain a near constant voltage across the load.
- The variation of this series impedance is controlled by a feedback amplifier that compares the output changes against the reference source to produce the control voltage.
- The operational description of various series regulators is given in the lesson 2 notes.
- The equations for the analysis of various series regulators is given in the lesson 2 notes.
- A series regulator may have a fixed or user set output voltage within designed limits.
- The error amplifier may be a simple single transistor, differential circuit or an OP. AMP. with the more complex circuit giving better regulation.
- To help minimise the drive current requirements of the error amplifier system a DARLINGTON connection of two or more transistors may be used in the series pass part of the circuit.
- Since a series pass transistor may be required to dissipate considerable power, a heat sink is frequently required and hence replacement procedures for faulty components should be adhered to.
- The greater the difference between the input voltage and the regulated output voltage, the greater the dissipation of the series pass transistor.
- Voltage analysis may differ slightly for the different styles of error amplifier and if Darlington transistor configurations are used

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LESSON 3. - OVERLOAD PROTECTION UEE30911

- Once a series regulator has reached its maximum designed current capability, current overload protection is required if excessive power dissipation is to be avoided in both the load and series pass device.
- Overload protection of a series regulator can be of a *CONSTANT CURRENT* variety or it may be *FOLDBACK CURRENT LIMITED.*
- Constant current limiting may use diode protection or transistor protection. The transistor type tends to operate with a sharper cutoff.
- Constant current limiting depends on a clamping action that stops the error amplifier from correcting the output voltage variation.
- The current limit value can be approximated from I(limit) = 0.7V/R(sense)
- The current limit can be made user adjustable by the addition of suitable resistors.
- Foldback current limiting can be obtained by the addition of two resistors.
- The foldback current limit sense resistor value is modified in value if compared to the constant current limit value and can be a calculated from the equations given in lesson 3 of the notes.
- The short circuit current of a foldback current limited supplies may be 1/3 or less of its maximum.
- Sensitive equipment may be damaged if a fault develops that lets the regulated output voltage exceed a specified maximum. Over voltage protection can be arranged that removes the supply if that specified maximum is exceeded.

LESSON 4. - I.C. VOLTAGE REGULATORS

- A number of *INTEGRATED CIRCUIT* regulators are available that have excellent load and line regulation performance and the ripple reduction.
- The 723 type regulator can be used in a number of configurations with either constant current or foldback current limiting.
- External pass transistors can be added to obtain a greater current capability to the 723 regulator .
- The equations for analysis are shown on page 2 lesson 4
- The three terminal regulator can be used to produce a minimal component regulator but a few external components and the 'precautions in use' should be adhered to. (Page 3 lesson 4).
- Both positive and negative voltage versions of three terminal regulators are available.
- Three terminal regulators can be obtained in a number of packages that have specified current ratings.
- Negative regulators may not have the same pinout connections as positive regulators.

LESSON 5. - NON-STANDARD AND VARIABLE OUTPUT 3 TERMINAL REGULATORS

- Non-standard output voltage can be obtained from three terminal regulators by the addition of two external resistors.
- The equations for these non-standard voltages are shown in page 1 of lesson 5.

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LESSON 5 - Cont. UEE30911

- For continuously variable output voltage, special three terminal regulators are available that have been manufactured to minimise the quiescent current in the common leg.
- Extra components are added to give further protection of variable type three terminal regulators. (See page 2 of lesson 5 notes)
- Outboard pass transistors can be added to increase the current capability of three terminal regulators. (See page 3 of lesson 5 notes)
- Precision voltage regulators are available that can be set to an accurate voltage by a single selected resistor value. (Page 4 of lesson 5 notes)

LESSON 6 - SWITCHED MODE REGULATORS

- Switched mode voltage regulators operate with an active device that switches between saturation and cutoff with a defined mark space ratio and a magnetically charged inductor or transformer that releases its energy into the load and filter capacitance.
- The mark/space ratio is controlled by an error amplifier/reference system.
- The switching frequency may be anywhere from a few kiloHertz to hundreds of kiloHertz.
- Because of the frequencies involved, the filtering components can be smaller and lighter.
- Radio frequency interference may be a problem with some SMPS systems.
- The single ended *STEP DOWN* regulator is described on page 2 of lesson 6 notes along with the main equations for finding Vout.
- Diodes and transistors used in SMPS applications require to be capable of very fast switching speeds.
- The single ended *STEP UP* regulator and equation is described on page 3 of lesson 6.
- The single ended *INVERTING* regulator and equation is described on page 4 of lesson 6.

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LESSON 7 - PULSE WIDTH MODULATOR PRINCIPLES

- The *PULSE WIDTH MODULATOR* may utilise a comparator circuit and a triangular wave generator to produce the variable mark/space ratio pulse generator.
- An example of such a system is described on pages 1 and 2 of lesson 7 notes.
- The method described is an example of a fixed frequency/variable mark/space ratio type of SMPS.
- PNP chopper transistors are often used in SMPS positive voltage applications as the circuit efficiency is improved.
- The exact circuit may vary in the above type of supply, particularly in IC SMPS applications.
- Another method of varying the effective mark/space ratio is to set a constant 'ON' time and vary the frequency of the oscillator.
- Current overload is a feature of IC style SMPS systems that cause the chip to stop oscillating or to remove drive to the chopper transistor.
- The inductor and capacitor combination is a critical design area of a SMPS.
- SMPS's need to operate with a minimum load current otherwise they may give poor ripple performance.

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LESSON 8 - TRANSFORMER COUPLED SMPS's UEE30911

- Single ended transformer coupled SMPS's operate in the *FLYBACK* mode or the *FORWARD* mode.
- In the flyback mode, the input energy is stored in the transformer's magnetic field while the chopper is conducting and release to the load and filter circuit when the chopper is cutoff.
- A description of a flyback circuit is on page 1 of lesson 8 notes.
- The flyback circuit can be used for stepping up, stepping down or inverting the output voltage.
- If a high and dangerous voltage is applied to the input such as an *OFF LINE* circuit where the mains is rectified directly, an *OPTO-ISOLATOR* may be used between the chopper and the error amplifier circuit.
- In the forward mode of operation, the input energy is switched through the transformer to the load and energy storage inductor while the chopper is conducting. When the chopper switches off, the energy in the storage inductor is released to the load with the aid of a *FREE WHEEL* diode.
- A description of a forward converter is on page 2 of lesson 8 notes.
- Push pull operation of transformer coupled power supplies can be used where the power output is considered too much for a single ended circuit.
- The drive waveform for push pull operation requires a small *DEAD BAND* to be inserted in the drive waveform to allow one transistor to switch off before switching the other one on.
- A single primary winding requires a *BRIDGE* or *HALF-BRIDGE* configuration of the switching transistors but needs a drive transformer with multiple secondaries.
- A centre tapped primary winding can use two transistors in a push pull configuration that simplifies the drive requirements.
- The filter capacitor of SMPS's may be applied as several units in parallel to minimise the *EQUIVALENT SERIES RESISTANCE* to improve the ripple performance and to reduce local heating effects in the capacitors.
- The filter capacitors may be further improved by adding a small plastic or ceramic capacitor to reduce the effects of EQUIVALENT SERIES INDUCTANCE.
- Off line power supplies require the use of a *HASH FILTER* to reduce the possibility of interference travelling down the mains power lines.
- Sometimes, in critical ripple and regulation applications, a SMPS is used to *PRE-REGULATE* the voltage applied to a linear regulator to gain the advantage of having the efficiency of the former and the regulation and ripple reduction of the latter.

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TUTORIAL QUESTIONS

Answer TRUE or FALSE to the following statements.

- A shunt regulator dissipates the most power when fully loaded. [ ]
- With a fixed input voltage, a shunt regulator draws a constant current under all load conditions [ ]

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TUTORIAL Cont.

- Some voltage regulators dissipate zero power when delivering full load current. [ ]
- The control element of a shunt regulator will 'short circuit' if the output terminals are shorted together. [ ]
- The load regulation of a regulator circuit is how the input voltage affects the output voltage. [ ]
- All voltage regulators require that the input voltage be higher than the output voltage. [ ]
- The greater the difference between the input voltage and the output voltage of a series regulator the greater the dissipation of the regulator. [ ]
- A decrease in load voltage due to an increased load current of a series regulator causes an increase in the impedance of the series pass element. [ ]
- A band gap reference if often used in voltage regulators because it is available in any desired breakdown voltage. [ ]
- Darlington transistors tend to produce better a regulation characteristic in a series regulator because of their high inherent voltage gain. [ ]
- A heatsink functions by allowing the total heat produced at the collector of a regulating element to be conducted away to a larger surface area. [ ]
- Constant current overload protection reduces the dissipation of the series pass element if the output terminals are shorted together. [ ]
- When the current overload circuit is activated in a series regulator, it removes control of the system from the error amplifier. [ ]
- When foldback current limiting is used the short circuit current is smaller than the maximum load current. [ ]
- Over voltage protection, when operated, simply removes the output voltage of the regulator from the load circuits. [ ]
- IC type series regulators can only be used with one polarity of input voltage. [ ]
- Three terminal regulators require external current limit protection. [ ]
- External pass transistors can be added to IC regulators to increase their current capability. [ ]

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TUTORIAL Cont. UEE30911

- Fixed voltage, three terminal regulators can be operated at other voltages by placing a zener diode in the common leg. [ ]
- Switched mode voltage regulators operate with high efficiency because the chopper only dissipates significant power while cutoff. [ ]
- In a flyback mode of operation, the input energy of a switched mode regulator is stored in the inductance of the system. [ ]
- The output filter capacitor of a switched mode regulator is often constructed of several smaller values in parallel. [ ]
- A switched mode regulator must be operated at a fixed frequency. [ ]
- For push pull type switched mode regulators, both transistors are switched together. [ ]
- The output filter of switched mode regulators are often further bypassed by a small value plastic capacitor to reduce the effects of equivalent series resistance. [ ]
- Electromagnetic interference is reduced by operating the switched mode regulator at a higher frequency. [ ]
- A switched mode regulator is sometimes used as a pre-regulator for a linear type regulator to improve the overall efficiency of the system. [ ]
- A 'free wheel' diode in a switched mode regulator is conducting while the chopper transistor is not conducting. [ ]
- Bridge type switched mode regulators can operate without the use of a centre tapped primary on the switching transformer. [ ]

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Review questions UEE30911

These questions will help you revise what you have learnt in Section 6.

Tick the correct box.

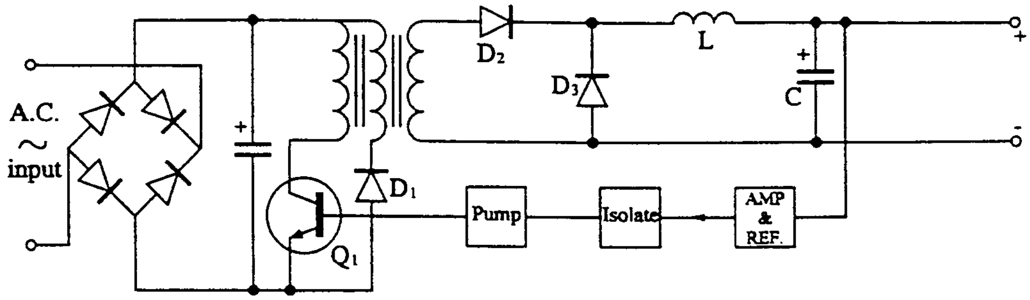

Fig. 1

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1. Refer to the circuit in Fig. 1. This block diagram shows a switched mode voltage regulator that can be described as a:

- ☐ flyback circuit
- ☐ forward circuit
- ☐ boost circuit
- ☐ full wave circuit.

2. Refer to the circuit in Fig. 1. Diode D1 is used in this circuit to:

- ☐ rectify the output pulse
- ☐ minimise saturation effects in the transformer
- ☐ increase the breakdown voltage of the transistor
- ☐ reverse bias the transistor during the 'off' time.

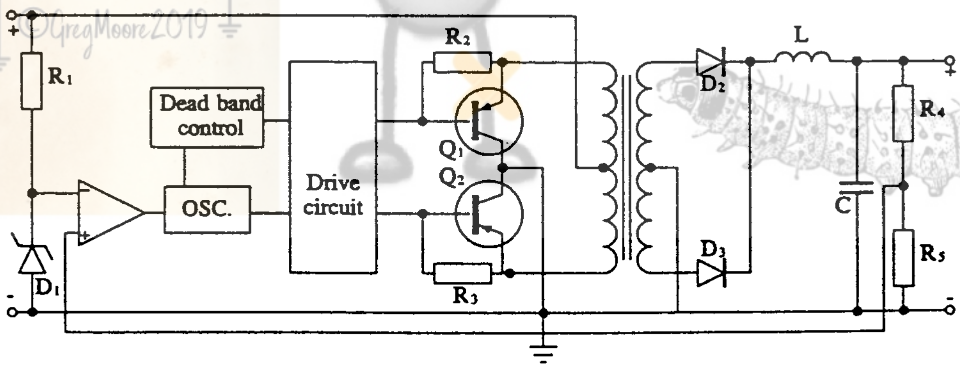

Fig. 2

3. Refer to the circuit in Fig. 2. This block diagram is described as:

- ☐ a flyback switching regulator
- ☐ a push pull forward regulator
- ☐ an isolated switching regulator
- ☐ an 'off line' switching regulator.

4. Refer to the circuit in Fig. 2. The block marked 'dead band control' is needed to:

   - ☐ keep the oscillator at the correct frequency
   - ☐ keep the drive circuit at the correct frequency
   - ☐ ensure one transistor is 'off' before turning the other one 'on'
   - ☐ allow the diodes to stop conducting before applying another pulse.

5. Refer to the circuit in Fig. 2. The effect of DC on the transformer is minimised in this circuit because:

   - ☐ diodes D2 and D3 block reverse current
   - ☐ of the high frequency of the circuit
   - ☐ each transistor is made to conduct for equal time
   - ☐ the feedback circuit isolates the input from the output.

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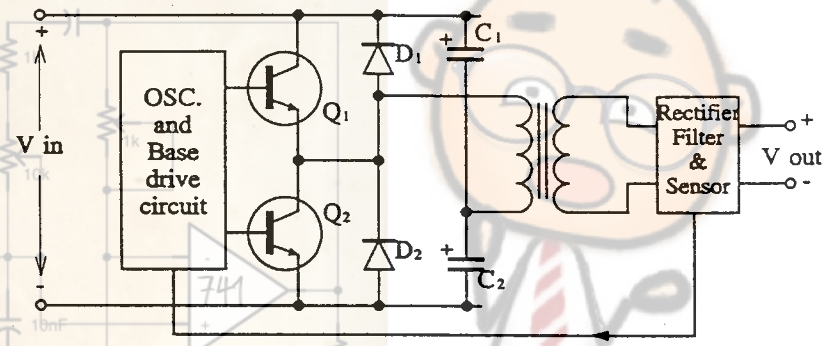

Fig. 3

6. Refer to the circuit in Fig. 3. This transistor configuration is described as:

   - ☐ floating forward converter
   - ☐ capacitive forward converter
   - ☐ full bridge forward converter
   - ☐ half bridge forward converter.

7. An 'off line' switched mode power supply is often used in TV applications because:

   - ☐ an expensive rectifier system is eliminated
   - ☐ a large value filter capacitor is eliminated
   - ☐ a 'mains' frequency transformer is eliminated
   - ☐ 'mains' frequency interference is eliminated.

Review questions

UEE30911

8. An 'off line' switched mode power supply requires that there be isolation:

- ☐ between the 'mains' supply and the rectified input DC voltage
- ☐ from the secondary of the switching transformer to the DC output
- ☐ between the DC output circuit and the switching circuit
- ☐ from the output sense circuit to the error amplifier circuit.

9. Switched mode power supplies tend to cause EMI because:

- ☐ the inductor radiates a large part of its contained energy into space
- ☐ fast switching of the active devices produce a large number of harmonics
- ☐ electrolytic capacitors have a high equivalent series resistance
- ☐ rectifiers tend to have a poor conduction recovery time at high frequencies.

10. The reason for using a switched mode regulator as a pre-regulator to a linear regulator circuit is to:

- ☐ eliminate the EMI generated by the switched mode supply
- ☐ improve the efficiency and power dissipation of the switched mode circuit
- ☐ improve the overall performance and efficiency of the linear circuit
- ☐ provide isolation of the load circuit from the switched mode circuit.

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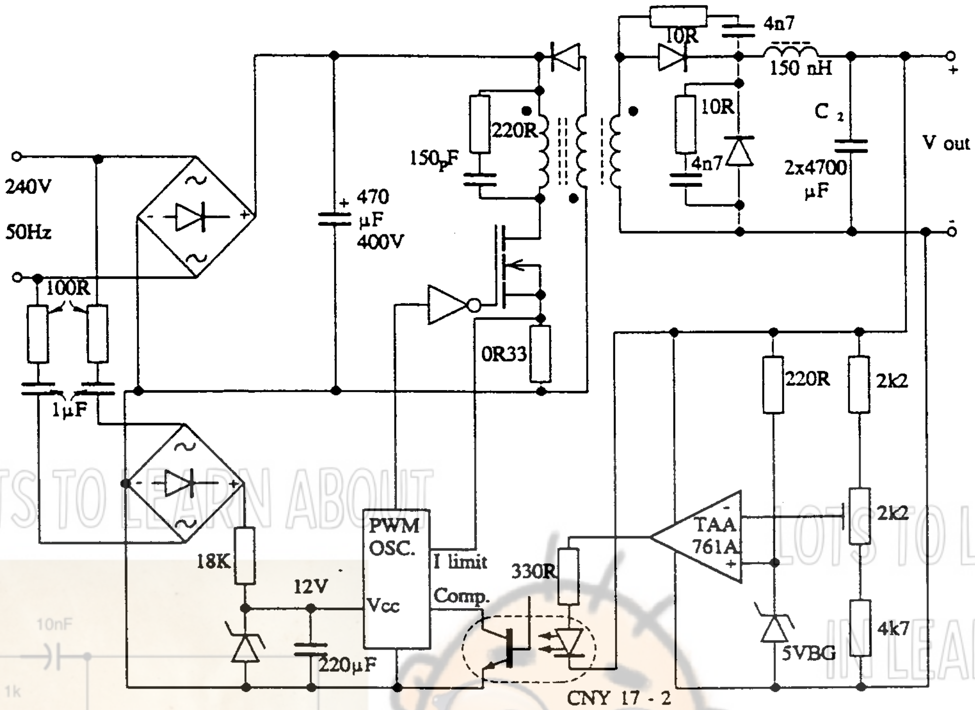

Fig. 4

11. Refer to the circuit in Fig. 4. State how isolation is achieved in this circuit and briefly describe how it operates.

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Review questions

12. Refer to the circuit in Fig. 4. The filter capacitor C2 is listed as being 2 times 4700uF. Briefly describe why two capacitors and not a single capacitor is used in this circuit.

13. Refer to the circuit in Fig. 4. Briefly describe how the transformer primary current is limited in this circuit.

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14. Refer to the circuit in Fig. 4. Assuming the circuit operates at 50 kHz, what important characteristic must apply to the output rectifier diodes.

15. Refer to the circuit in Fig. 4. The output is set to 5V. Briefly describe how this adjustment is achieved.